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RESEARCH MEMORANDUM

FLIGHT INVESTIGATION OF PENTABORANE FUEL IN 9.75-INCH-DIAMETER RAM-JET ENGINE WITH DOWNSTREAM FUEL INJECTION

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NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS
WASHINGTON
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RESEARCH MEMORANDUM

FLIGHT INVESTIGATION OF PENTABORANE FUEL IN 9.75-INCH-DIAMETER RAM-JET ENGINE WITH DOWNSTREAM FUEL INJECTION

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SUMMARY

The third flight test of pentaborane fuel in a 9.75-inch-diameter air-launched ram-jet engine with a design free-stream Mach number of 1.8 was made. The ram jet used for this test was equipped with a revised spray-bar - flameholder configuration. This change was designed to prevent burning upstream of the flameholder and thereby prevent fuel-spray-bar plugging, which was suspected to have occurred during the previous flight.

After release from the carrier airplane at an altitude of 33,600 feet and a free-stream Mach number of 0.51, the engine accelerated to a maximum Mach number of 2.06 in 34.1 seconds. A maximum acceleration of 7.2 g's was reached at the same instant. The propulsive thrust (thrust minus drag) coefficient reached a maximum value of 0.573 at a free-stream Mach number of 1.77, while the actual propulsive-thrust specific fuel consumption (based on the actual combustion efficiency) reached a minimum value of 2.44 pounds per hour per pound thrust minus drag at a free-stream Mach number of about 1.8. The calculated values of ideal propulsive-thrust specific fuel consumption (based on 100-percent combustion efficiency) of pentaborane for the actual propulsive thrust were essentially the same as the actual values at free-stream Mach numbers greater than 1.7, indicating combustion efficiencies in the order of 100 percent for that portion of the flight. The calculated values of ideal propulsive-thrust specific fuel consumption of octene-1 for the actual propulsive thrust were about 33 percent higher than those for pentaborane in the Mach number range from 1.7 to 2.06. The average equivalence ratio of pentaborane during this period was 0.33.

INTRODUCTION

Pentaborane is being evaluated as a ram-jet fuel by the NACA Lewis laboratory, through a series of test-stand and flight tests in cooperation with the Bureau of Aeronautics, Department of the Navy, as part of Project Zip. The flight tests are conducted by launching fin-stabilized,

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unguided 9.75-inch-diameter ram-jet engines from a carrier airplane at high altitude. Data are obtained during the free flight by means of radar and telemetering. The first flight test (ref. 1) was made at a comparatively rich fuel-air ratio (equivalence ratio ≈ 0.55). The second flight test (ref. 2) was made at an equivalence ratio of about 0.23. It is believed that a decline in thrust, which the second flight test engine experienced as it approached a Mach number of 1.8, was caused by a plugging of the fuel-spray bar. In order to prevent this plugging a revised spray-bar - flameholder configuration was installed in the third flight engine. The revisions, which were made to prevent burning upstream of the flameholder, consisted of shortening the flameholder, redesigning the fuel injector to spray angularly downstream from 48 holes instead of upstream from 24 holes, and jacketing the fuel-injector tubes with a steel fairing. The results of the flight of this thrid engine are reported herein. 3852

SYMBOLS

The following symbols are used in this report:

A_{max}	maximum cross-sectional area, 0.536 sq ft
a_n	axial acceleration (exclusive of gravity component), g's
C_D	drag coefficient, D/q_0A_{max}
C_F	thrust coefficient, F/q_0A_{max}
$C_F - C_D$	propulsive thrust coefficient
D	drag, lb
F	thrust, lb
M	Mach number
P	total pressure, lb/sq ft abs
PSFC	propulsive-thrust specific fuel consumption, lb/(hr)(lb thrust-drag)
p	static pressure, lb/sq ft abs
q	dynamic pressure, $0.7\ pM^2$, lb/sq ft
Re	Reynolds number based on body length of 9.61 ft
T	total temperature, ^{o}R

t static temperature, $^{\circ}R$

V velocity, ft/sec

W_e engine weight at any given instant, lb

w_f fuel flow, lb/hr

η_c combustion efficiency

τ total-temperature ratio, T_6/T_0

φ equivalence ratio, ratio of actual to stoichiometric fuel-air ratio

Subscripts:

actual conditions with actual combustion efficiencies

ideal conditions with 100-percent combustion efficiency

0 station at free stream

1 station at inlet

2 station in diffuser $20\frac{9}{16}$ in. downstream of inlet

3 station in diffuser $64\frac{5}{8}$ in. downstream of inlet

4 fictitious station which has the same total pressure and air flow as station 3 but has an area equal to that at station 5

5 station immediately downstream of flameholder

6 station at exit

APPARATUS AND INSTRUMENTATION

A photograph of the ram-jet engine mounted on the carrier airplane is shown in figure 1. A sketch of the engine, which has a design free-stream Mach number of 1.8, is shown in figure 2. The engine was the same as that described in reference 2 with the following exceptions:

(1) The wedge-shaped flameholder elements were cut off 3 inches from the downstream end. A photograph of the revised flameholder is shown in figure 3.

(2) The fuel injector was redesigned to spray angularly downstream from 48 holes instead of upstream from 24 holes.

(3) The radial fuel-injector tubes were jacketed with a 0.018-inch-gage steel fairing. A photograph of the revised injector is shown in figure 4, and a sketch is presented in figure 5.

These changes in the flameholder and the fuel injector, which were intended to prevent burning upstream of the flameholder and thus forestall plugging of the fuel injector, were developed through ground tests similar to those reported in reference 3. 3852

The weight of the engine at launching was 142 pounds. This weight included 8.8 pounds of fuel and 2.5 pounds for ignition flares which ejected from the engine during flight.

The instrumentation consisted of an eight-channel telemetering unit which was identical to that described in reference 2.

CALCULATION PROCEDURE

At the completion of the ram-jet flight, the atmospheric pressures and temperatures and the wind velocities throughout the altitude range of the flight were determined by means of a radiosonde type instrument. The free-stream Mach number of the ram jet was calculated from the ratio of the free-stream static to total pressure, both of which were measured at the Pitot-static tube protruding from the nose of the engine centerbody. In the supersonic Mach number range, normal-shock corrections were applied to the measured total pressure in order to obtain the free-stream total pressure. The free-stream static pressure was also obtained from the atmospheric survey and the altitude of the ram jet as determined from the radar data. The absolute velocity of the engine was determined from the radar data and also from the telemetered accelerometer data. In both cases the wind velocity was applied to the absolute velocity in order to determine the velocity relative to the air. The free-stream velocity was also calculated from the free-stream Mach number and the speed of sound. The agreement was within 2 percent for all three methods. The free-stream Mach number, total temperature, and total pressure were calculated by the methods described in reference 4.

The propulsive thrust (thrust minus drag) coefficient was obtained from the equation

$$C_F - C_D = \frac{F - D}{q_0 A_{max}} \tag{1}$$

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where

$$F - D = W_e a_n \tag{2}$$

The measured fuel pressure, which indicated impossibly low fuel flows, was considered to be in error and was not used. Instead, the fuel flow was calculated from a preflight calibration of the fuel system. The calibration was made on a basis of fuel flow against the fuel regulator signal pressure, which was the total pressure measured at the Pitot-static tube. As a check, the total fuel flow based on the measured total pressure during the flight was calculated and found to be within 5 percent of the fuel-tank capacity.

The propulsive-thrust specific fuel consumption, which is defined as the pounds of fuel per hour per pound of thrust minus drag, was calculated from the equation

$$PSFC = \frac{w_f}{F - D} \tag{3}$$

The combustor inlet and exit flow conditions during the flight could not be calculated directly from the telemetered data because of discrepancies in the measured internal airflow and in the measured total pressure at station 4. For this reason, the combustor flow conditions were obtained from calculations of thrust minus drag as a function of combustor parameters in the following manner:

At a given flight condition of Mach number and altitude, values of thrust-minus-drag coefficient were calculated for various ideal equivalence ratios using the gas properties given in references 3 and 5. In calculating the thrust coefficient, the total-pressure drop between stations 2 and 4 with critical or subcritical flow was assumed to be equal to 25 percent of the dynamic pressure at the inlet. This assumption is based on the results from references 1 and 2 and on low-speed duct tests of the subsonic diffuser. The total-pressure drop across the flameholder was assumed to be equal to 1.2 times the dynamic pressure upstream of the flameholder ($P_4 - P_5 = 1.2\ q_4$). This assumption is based on the results of reference 3 and low-speed duct tests. The drag coefficient for each flight condition was estimated from the data of references 6 and 7. By plotting curves of the calculated combustor parameters, such as exit temperature, inlet Mach number, ideal equivalence ratio, heat addition, and so forth, against the corresponding calculated values of thrust-minus-drag coefficient, it was possible to determine the specific values of these parameters which corresponded to the actual thrust-minus-drag coefficient as determined from the accelerometer data. These calculated values are shown at free-stream Mach numbers above 1.25 where the combustor exit is choked. Under subchoking conditions, with the exit Mach number variable, these calculations are of questionable accuracy.

The propulsive-thrust specific fuel consumption for 100-percent combustion efficiency was then calculated from the equation

$$PSFC_{ideal} = \frac{w_{f,ideal}}{(F - D)_{actual}} \qquad (4)$$

An indication of combustion efficiency would then be

$$\eta_c = \left(\frac{PSFC_{ideal}}{PSFC_{actual}}\right)_{(F-D)=constant} \qquad (5)$$

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RESULTS AND DISCUSSION

The results of the third flight of a pentaborane-fueled ram-jet engine by the NACA Lewis laboratory are plotted against time or free-stream Mach number.

The time histories of the flight conditions are presented in figure 6. Included in the figure are curves of axial acceleration (exclusive of gravity component), free-stream Mach number, altitude, free-stream total and static temperatures, free-stream total and static pressures, and Reynolds number. The Reynolds number is based on a body length of 9.61 feet. After release from the airplane at an altitude of 33,600 feet and a free-stream Mach number M_0 of 0.51, the ram jet accelerated to the design free-stream Mach number of 1.8 in 33 seconds. The altitude at this time was 12,500 feet. Positive acceleration continued until a maximum Mach number of 2.06 and a maximum axial acceleration of 7.2 g's were reached at 34.1 seconds. The altitude at peak Mach number was 10,600 feet. Camera films indicate that at this instant a large flash of flame emerged from the engine tailpipe. The accelerometer was affected by the severe vibrations and pulsations which followed to such an extent that no acceleration data could be read from the telemeter record. The Mach number curve, however, indicates that the engine, although still burning, began to decelerate quite rapidly. Three seconds later the fuel supply was exhausted and the engine decelerated at a higher rate until impact at 40.2 seconds after release. The steadily rising acceleration prior to 34.1 seconds indicates that the revised fuel-spray bar and flameholder performed satisfactorily during this flight.

It is believed that the loss of thrust at peak Mach number resulted from structural damage within the engine. Diffuser pressure measurements indicated a rapid drop in airflow at the same instant. This sudden drop in airflow could have been caused by deformation of the centerbody skin until it partially blocked the diffuser passage. The fact that the structural design Mach number of the engine was substantially exceeded gives added reason for believing that structural failure occurred.

The free-stream total pressure and total temperature reached maximum values of 11,640 pounds per square foot absolute and 942° R, respectively.

The time histories of the fuel flow and combustor-inlet static pressure and temperature are shown in figure 7. The area under the fuel-flow curve (fig. 7(a)) indicates a total fuel flow of 8.9 pounds. The total flow up to the peak Mach number was 6.4 pounds. These amounts include 0.3 pound of fuel which was consumed before the engine was released from the airplane.

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The combustor-inlet static temperature and pressure (fig. 7(b)) ranged from 487° to 930° R and from 1000 to 7800 pounds per square foot absolute, respectively, during the accelerating portion of the flight. The curves are shown as dashed lines to indicate that the values are derived from indirect calculations based on the propulsive thrust of the engine rather than calculations based on telemetered internal flow conditions.

Figure 8 presents the variation of the combustion-chamber conditions with free-stream Mach number. Included in the figure are curves of combustion-chamber total-temperature ratio, inlet velocity and Mach number, and actual and ideal equivalence ratio (equivalence ratio based on actual and on 100-percent combustion efficiency, respectively).

Propulsive Thrust

The propulsive thrust coefficient $(C_F - C_D)$ is presented in figure 9 as a function of M_0. As pointed out in the CALCULATION PROCEDURE section, the values of thrust minus drag are obtained directly from the telemetered acceleration data and do not depend on internal pressure measurements. It was also pointed out that the acceleration data were compared with the radar and Pitot-static tube data and found to agree within 2 percent.

The propulsive thrust coefficient reached a maximum value of 0.573 at a free-stream Mach number of 1.77. The curve falls off as the design-point Mach number is exceeded. However, because the rapidly rising dynamic pressure more than offsets the falling coefficient, the actual thrust-minus-drag force, as indicated by the acceleration, continued to rise up to peak Mach number. The effect of the transonic drag rise on the propulsive thrust coefficient is apparent in the shape of the curve between free-stream Mach numbers of 0.80 and 1.40. The estimated drag coefficient and the resulting thrust coefficient are also indicated in figure 9.

Propulsive-Thrust Specific Fuel Consumption

The propulsive-thrust specific fuel consumption based on the actual combustion efficiency is shown in figure 10 as a function of M_0. Also shown in the figure are curves of the ideal (100-percent combustion efficiency) calculated values for pentaborane and octene-1 based on the same thrust minus drag. At the design-point Mach number the actual PSFC reached a minimum value of 2.44 pounds per hour per pound thrust minus drag. This value increased slightly to 2.68 pounds per hour per pound thrust minus drag at the peak free-stream Mach number of 2.06. The ideal 3852
specific pentaborane consumption for the same flight conditions practically coincides with the experimental values at $M_0 > 1.7$, indicating that the engine was operating at approximately 100-percent combustion efficiency during this part of the flight. At lower Mach numbers, the accuracy of the ideal specific-fuel-consumption calculations is appreciably affected by possible errors in the estimated drag coefficient. For example, a 15-percent error in the estimated drag coefficient would involve a 25-percent error in the ideal PSFC at $M_0 \simeq 1.25$, but only an 8-percent error would result at $M_0 \simeq 1.8$. The ideal propulsive-thrust specific fuel consumption for octene-1 is about 33 percent higher than that for pentaborane in the Mach number range from 1.7 to 2.06. If lower combustion efficiencies resulted from the use of octene-1 than from pentaborane, or if a higher flameholder pressure drop was required for octene-1, the relative fuel consumption would then be even more favorable to pentaborane. The average equivalence ratio of pentaborane during the period when the Mach number went from 1.7 to 2.06 was 0.33. This equivalence ratio is in the range for pentaborane where heat is being absorbed by the vaporization of the solid oxides in the exhaust and, as was shown in flight 2, further improvements in fuel consumption are possible with lower equivalence ratios.

SUMMARY OF RESULTS

From the third flight test of pentaborane fuel in a 9.75-inch-diameter air-launched ram-jet engine with a design free-stream Mach number of 1.8, the following results were obtained:

1. A maximum free-stream Mach number of 2.06 was reached during the flight with a maximum axial acceleration (exclusive of gravity component) of 7.2 g's.

2. The propulsive thrust (thrust minus drag) coefficient reached a maximum value of 0.573 at a free-stream Mach number of 1.77.

3. The actual propulsive-thrust specific fuel consumption (based on the actual combustion efficiency) reached a minimum value of 2.44 pounds per hour per pound thrust minus drag at the design-point Mach number.

4. The calculated values of ideal propulsive-thrust specific fuel consumption (based on 100-percent combustion efficiency) of pentaborane for the actual propulsive thrust were essentially the same as the actual values at free-stream Mach numbers greater than 1.7, indicating combustion efficiencies in the order of 100 percent for that portion of the flight.

5. The calculated values of ideal propulsive-thrust specific fuel consumption of octene-1 for the actual propulsive thrust were about 33 percent higher than those for pentaborane in the Mach number range from 1.7 to 2.06. The average equivalence ratio of pentaborane during this period was 0.33.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, July 1, 1955

REFERENCES

1. Disher, John H., and Rabb, Leonard: Initial Performance Investigation of Pentaborane Fuel in Free-Flight Ram-Jet Engine. NACA RM E54D28, 1957.

2. Jones, Merle L., and Disher, John H.: Flight Investigation of Pentaborane Fuel in 9.75-Inch-Diameter Ram-Jet Engine at Low Equivalence Ratio. NACA RM E54L02, 1957.

3. Fivel, Herschel J., Tower, Leonard K., and Gibbs, James B.: Pentaborane Combustion Performance in 9.75-Inch-Diameter Ram-Jet Engine in Connected-Pipe Altitude Facility. NACA RM E54I16, 1957.

4. Carlton, William W., and Messing, Wesley E.: Free-Flight Performance of 16-Inch-Diameter Supersonic Ram-Jet Units. I - Four Units Designed for Combustion-Chamber-Inlet Mach Number of 0.12 at Free-Stream Mach Number of 1.6 (Units A-2, A-3, A-4, and A-5). NACA RM E9F22, 1949.

5. Tower, Leonard K.: Analytic Evaluation of Effect of Inlet-Air Temperature and Combustion Pressure on Combustion Performance of Boron Slurries and Blends of Pentaborane in Octene-1. NACA RM E55A31, 1955.

6. Messing, Wesley E., and Rabb, Leonard: Transonic Free-Flight Investigation of the Total Drag and of the Component Drags (Cowl Pressure, Additive, Base, Friction, and Internal) Encountered by a 16-Inch-Diameter Ram-Jet Engine for Mach Numbers from 0.80 to 1.43. NACA RM E52F02, 1952.

7. North, Warren J.: Summary of Free-Flight Performance of a Series of Ram-Jet Engines at Mach Numbers from 0.80 to 2.20. NACA RM E53K17, 1954.

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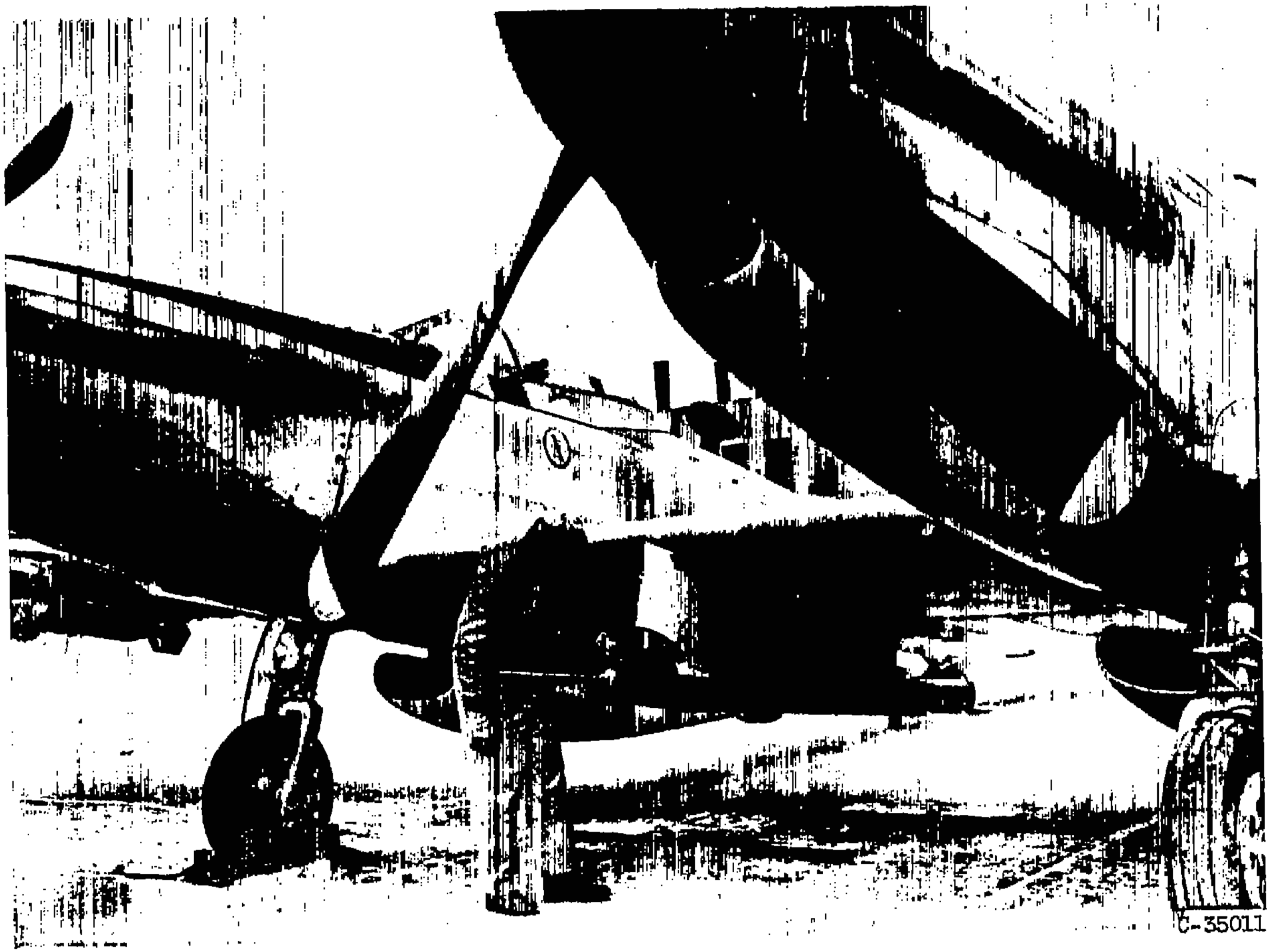

Figure 1. - 9.75-Inch-diameter ram-jet engine mounted on carrier aircraft.

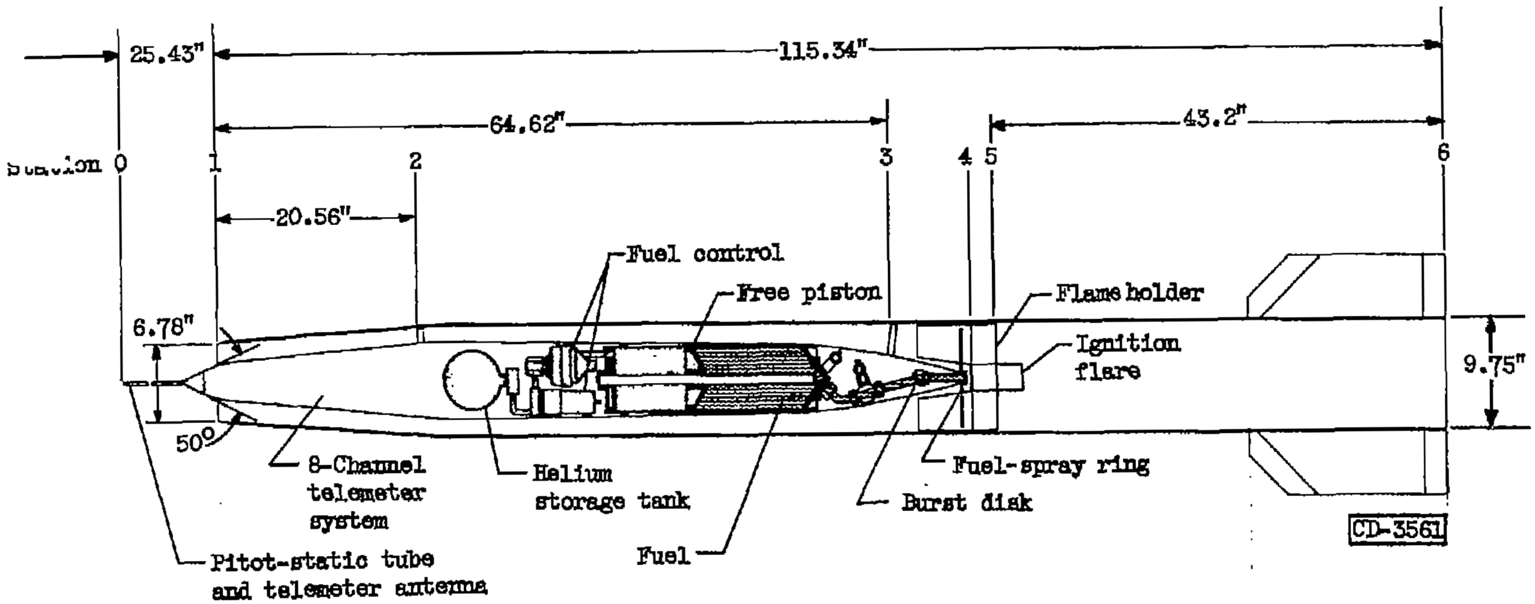

Figure 2. - Sketch of 9.75-inch-diameter free-flight ram-jet engine used in high-energy-fuel tests.

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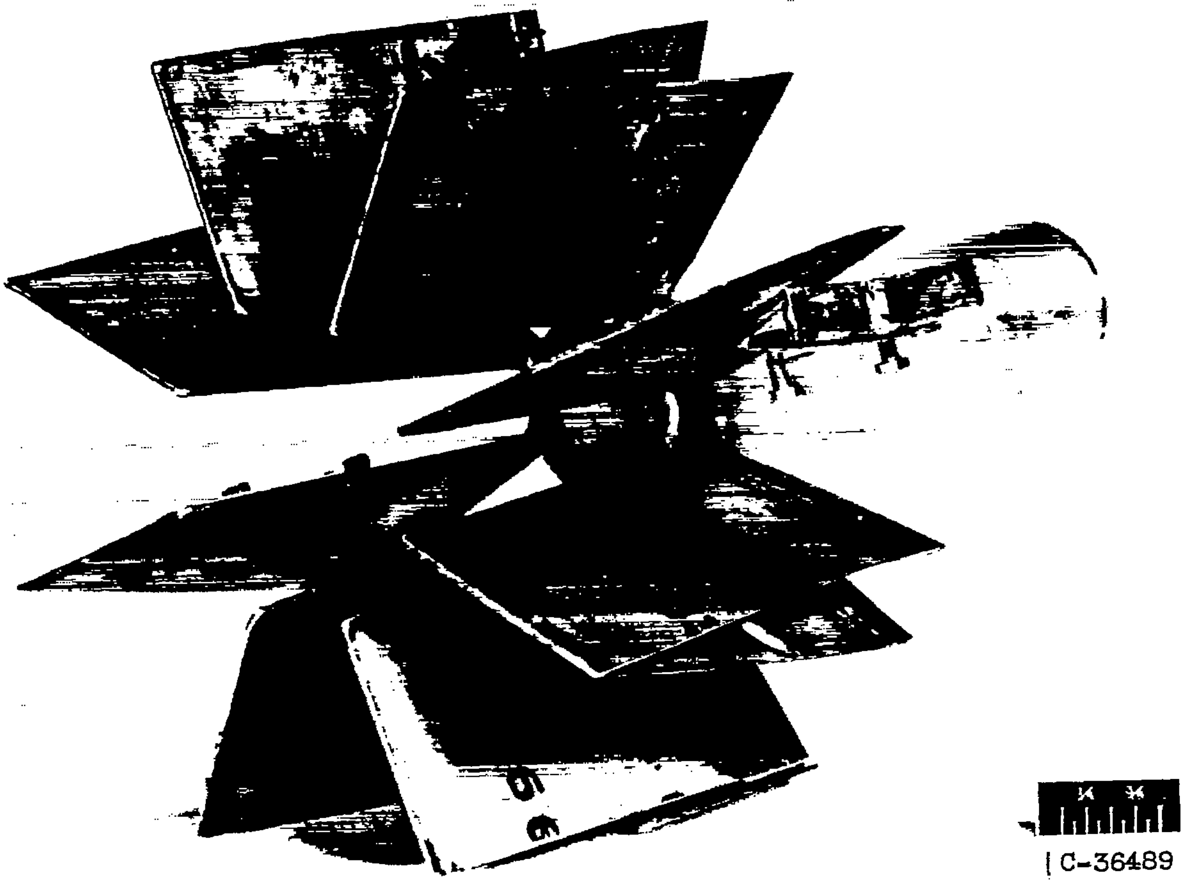

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Figure 3. - Flameholder and ignition flareholder.

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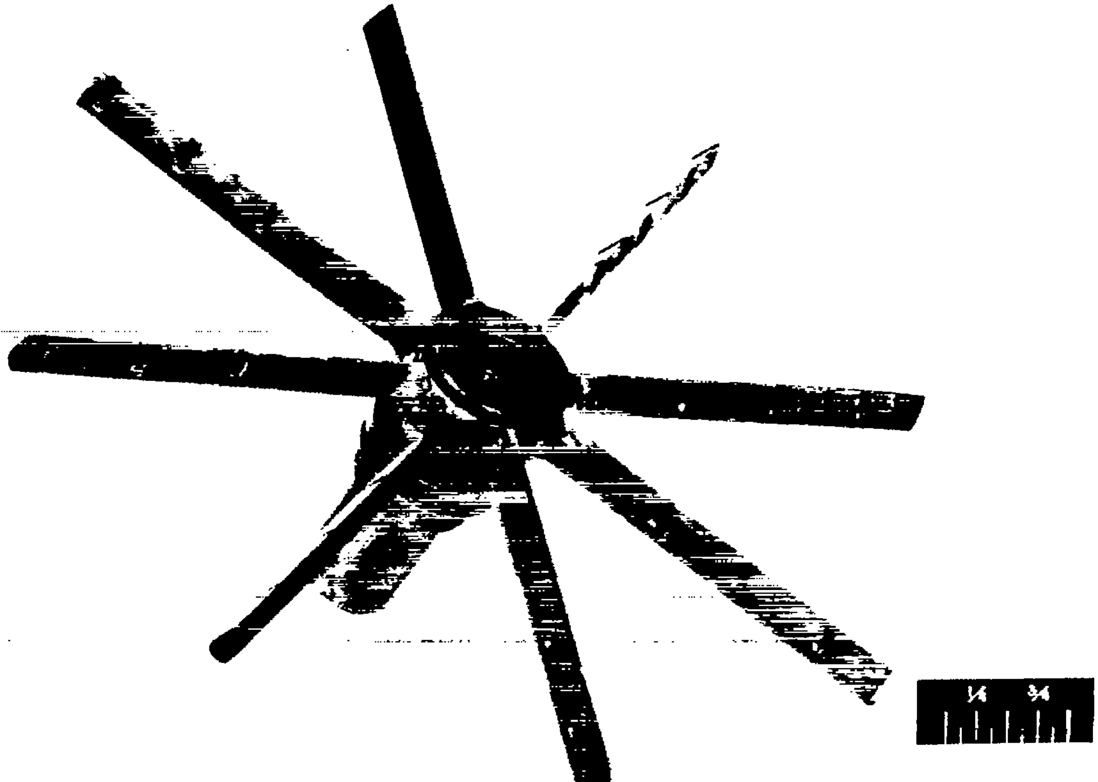

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Figure 4. - Fuel-spray bar.

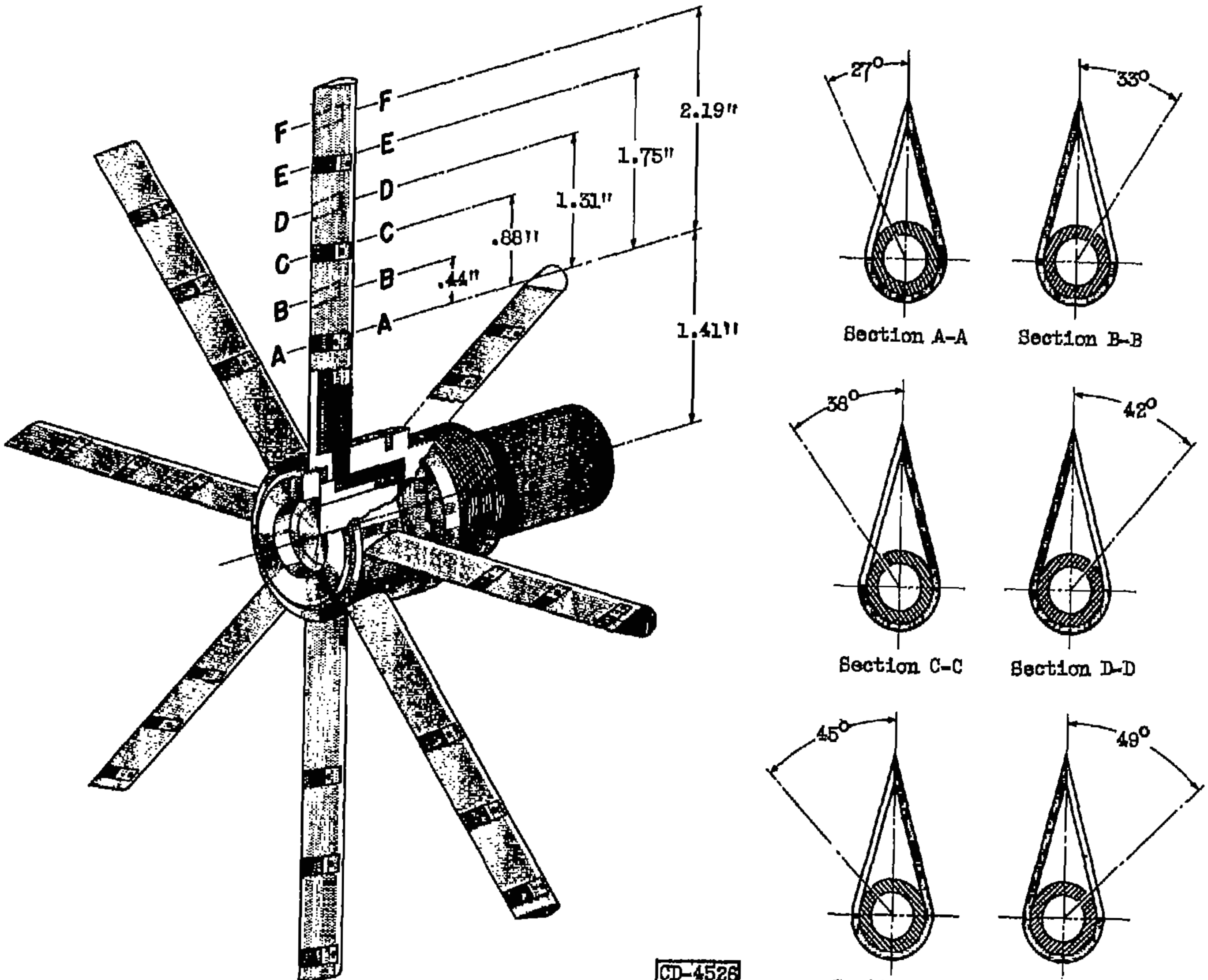

Figure 5. - Details of fuel-spray bar.

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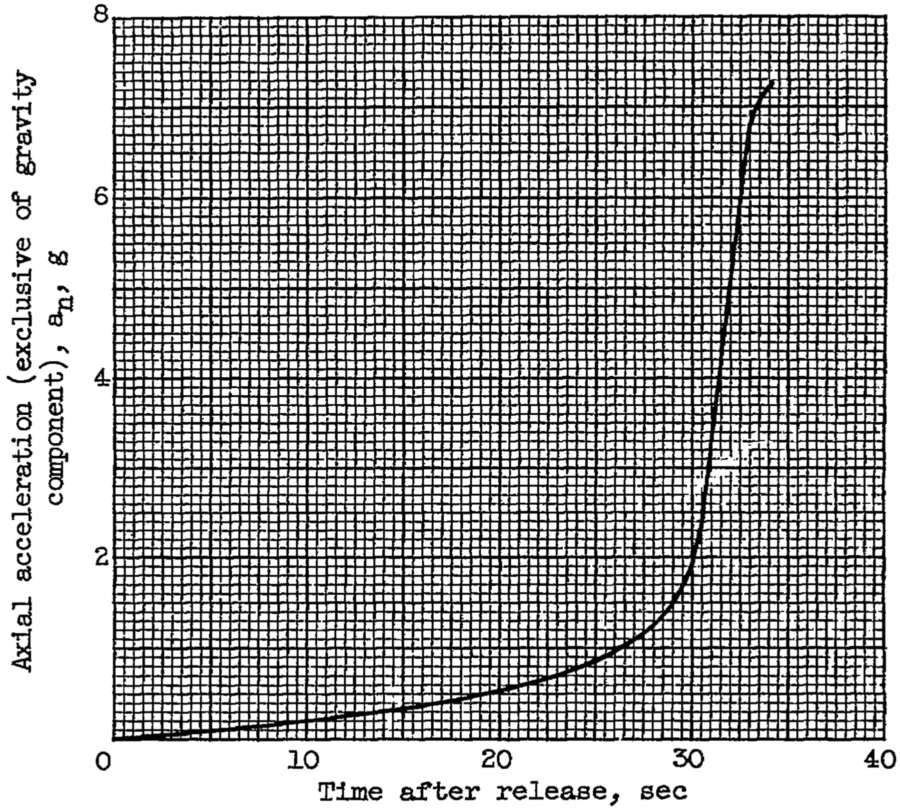

(a) Axial acceleration.

Figure 6. - Time history of flight conditions.

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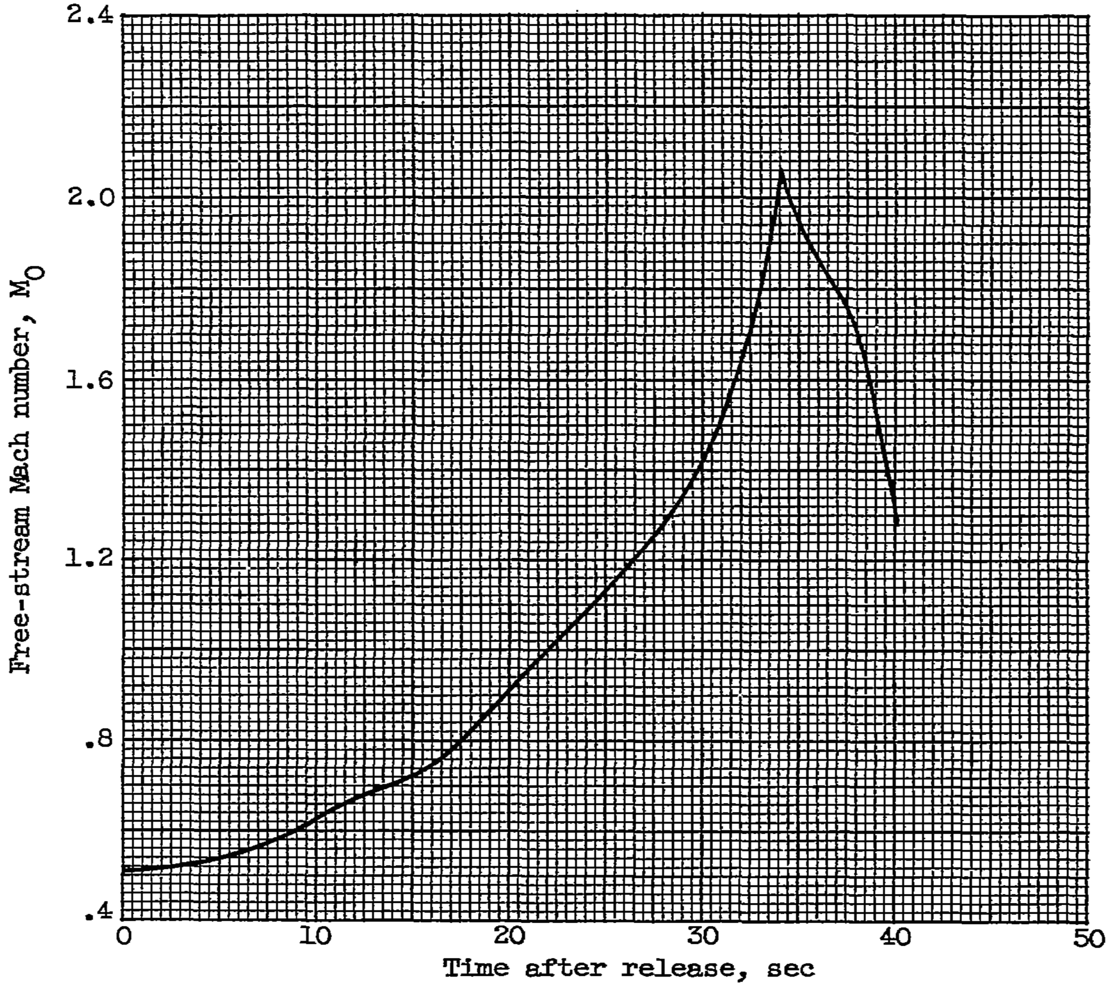

(b) Free-stream Mach number.

Figure 6. - Continued. Time history of flight conditions.

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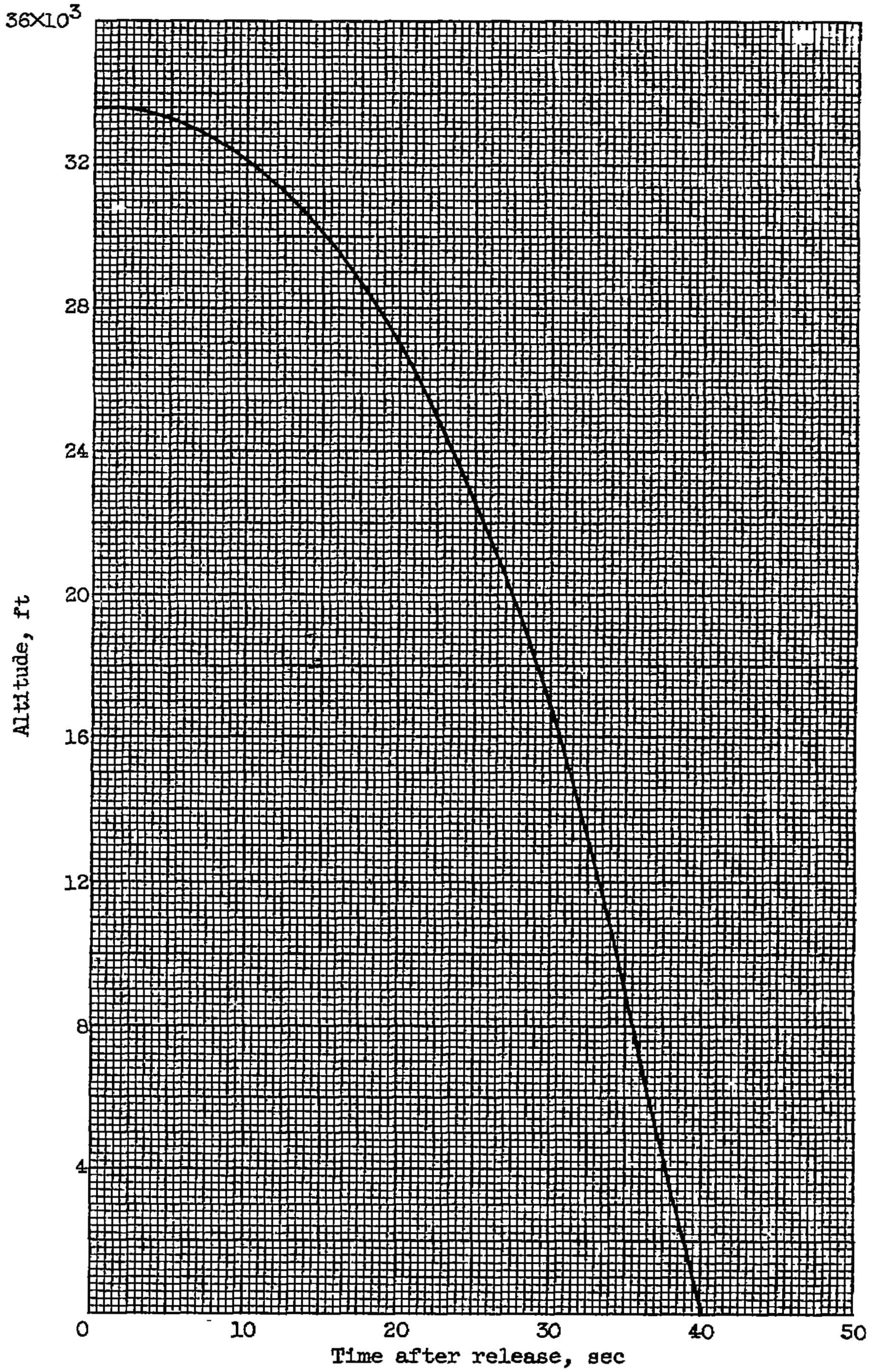
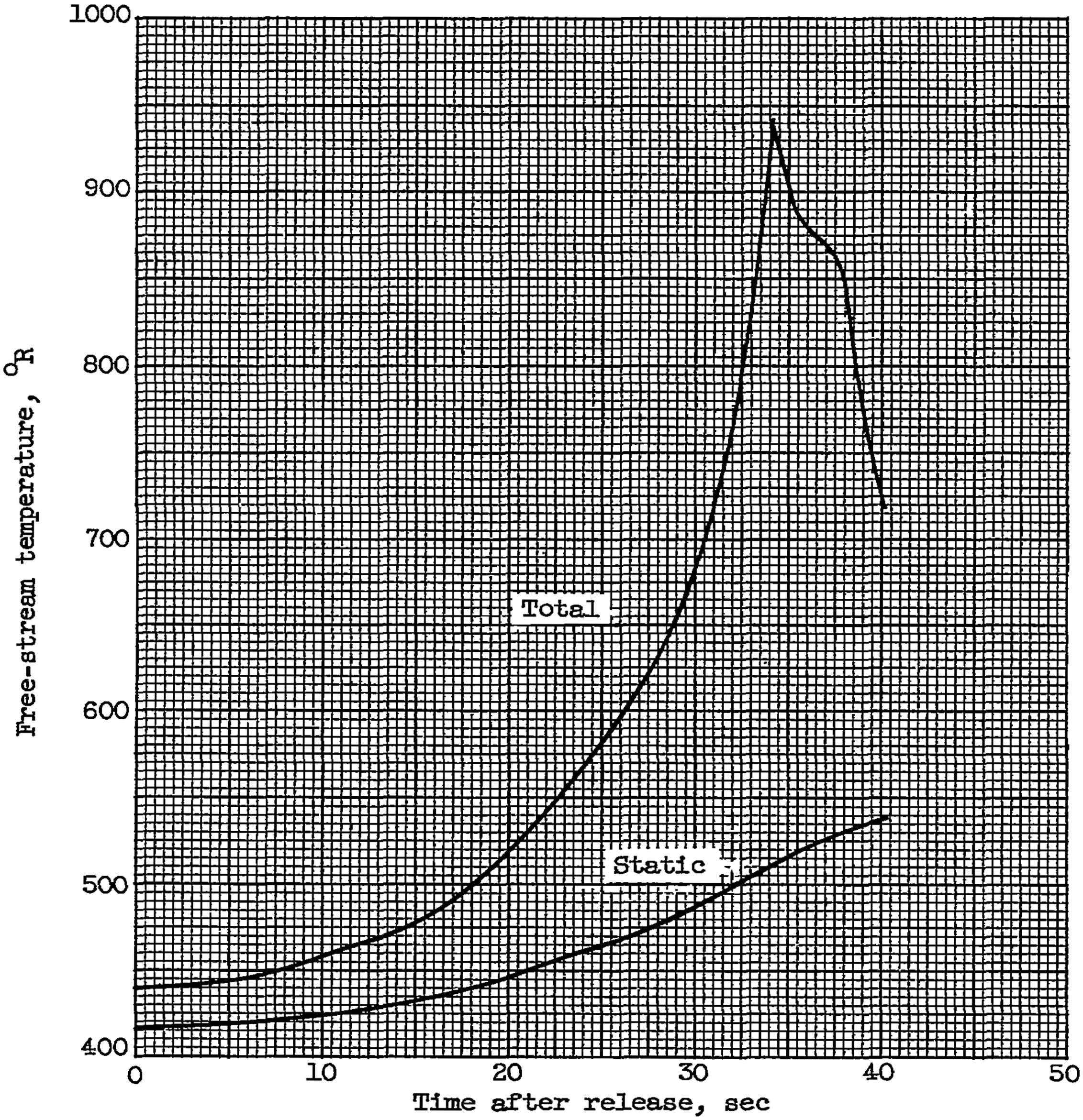


(c) Altitude.

Figure 6. - Continued. Time history of flight conditions.



(d) Free-stream temperatures.

Figure 6. - Continued. Time history of flight conditions.

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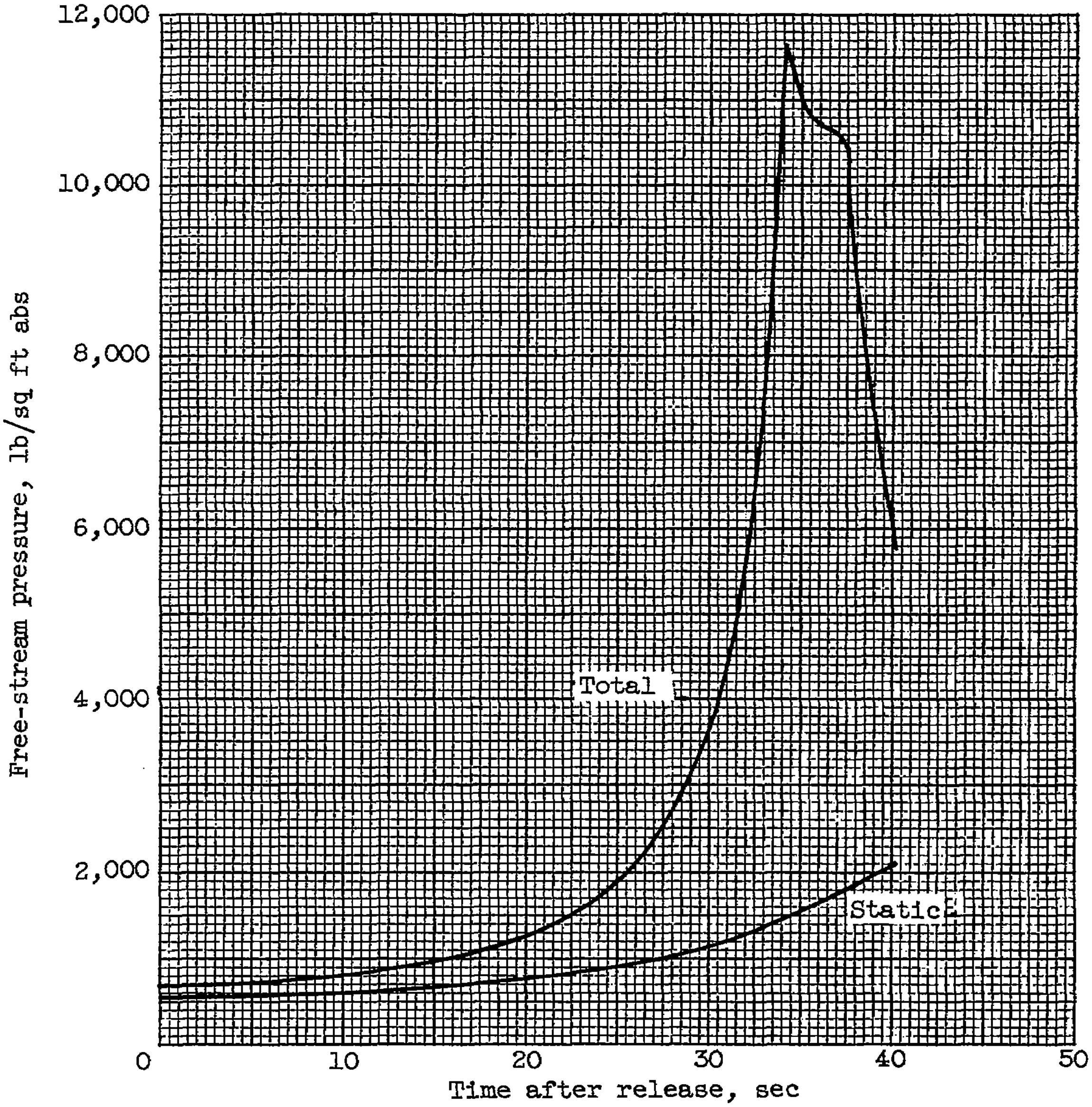

(e) Free-stream pressures.

Figure 6. - Continued. Time history of flight conditions.

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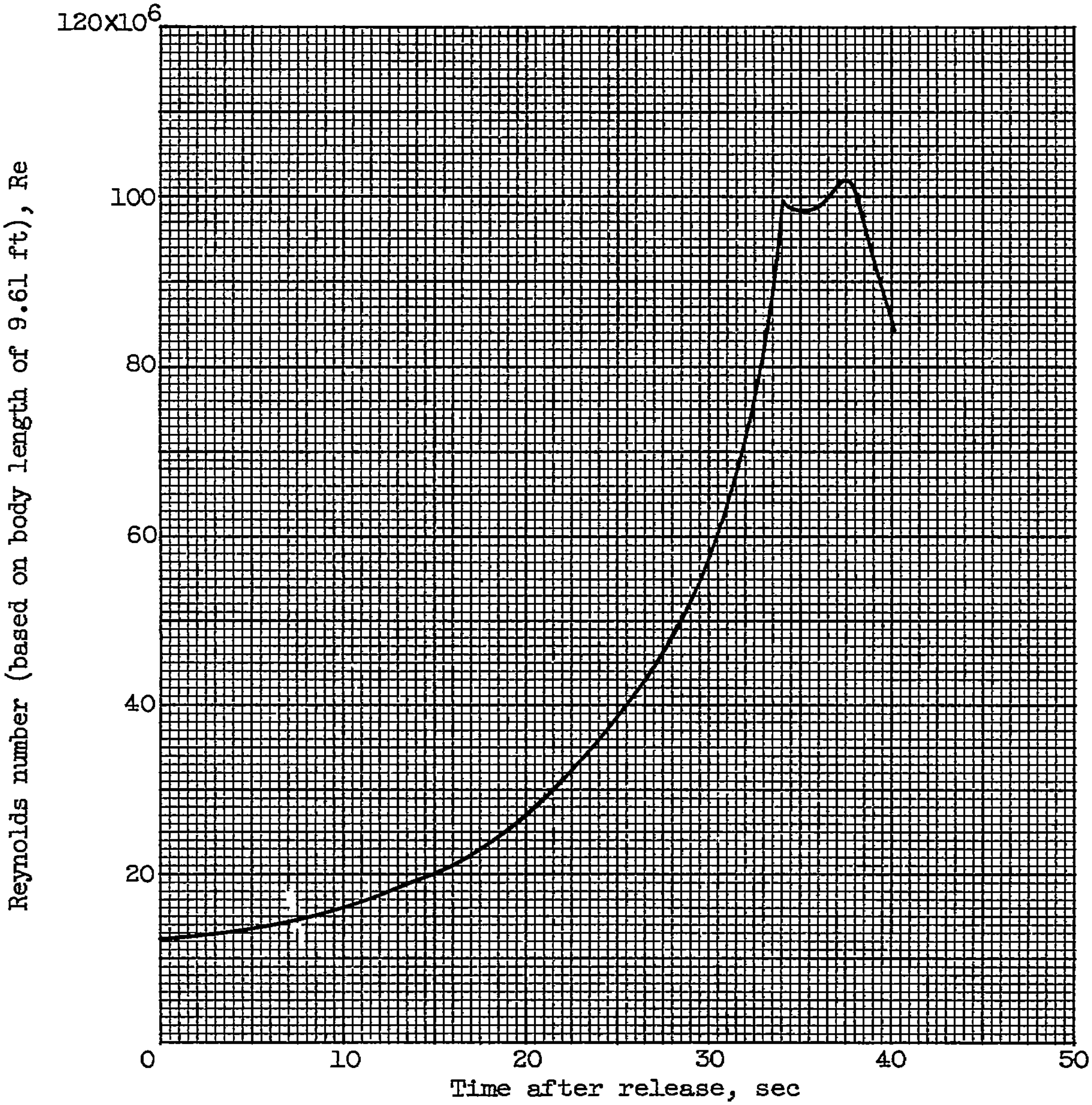

(f) Reynolds number.

Figure 6. - Concluded. Time history of flight conditions.

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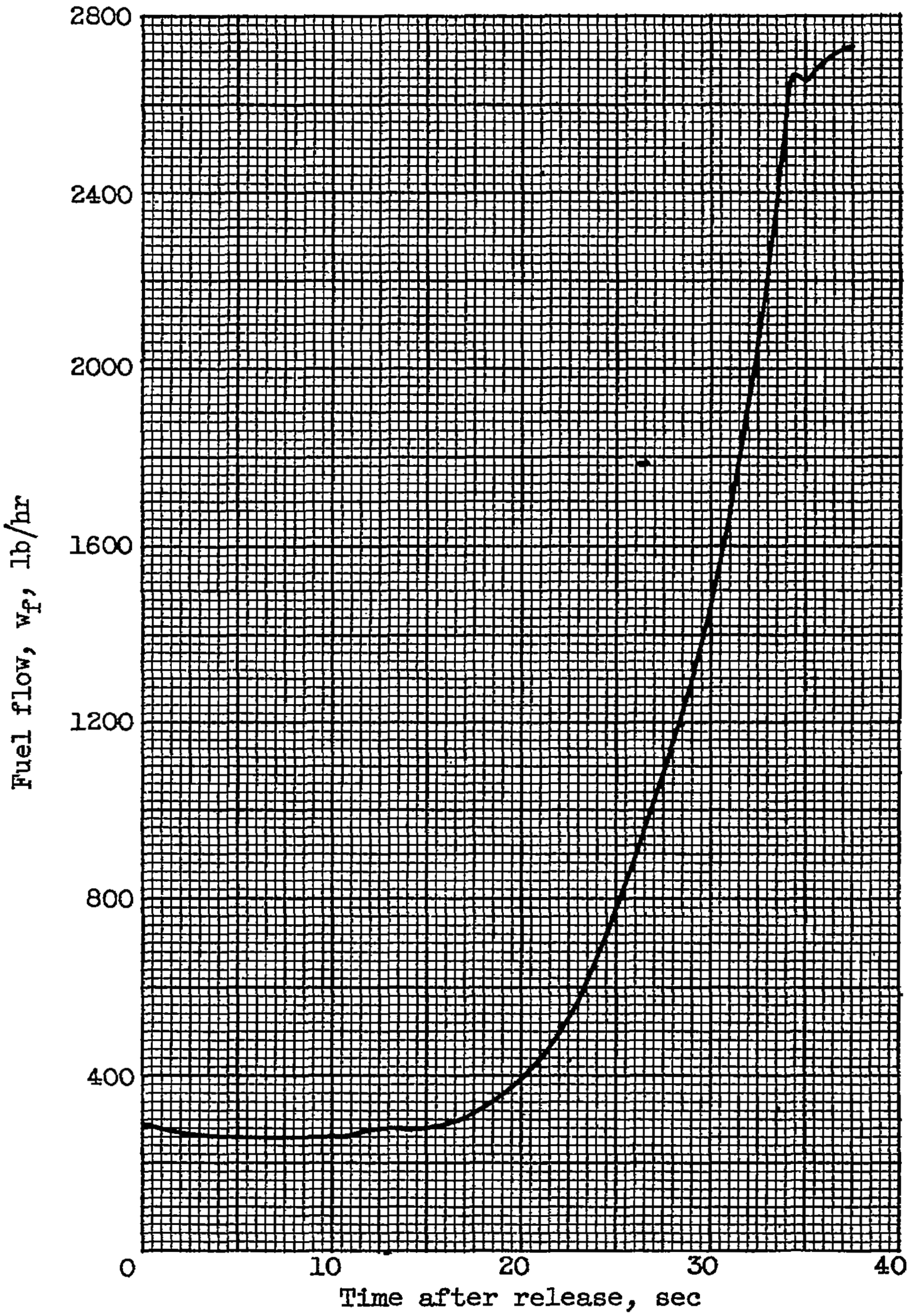

(a) Fuel flow.

Figure 7. - Time history of combustion-chamber conditions.

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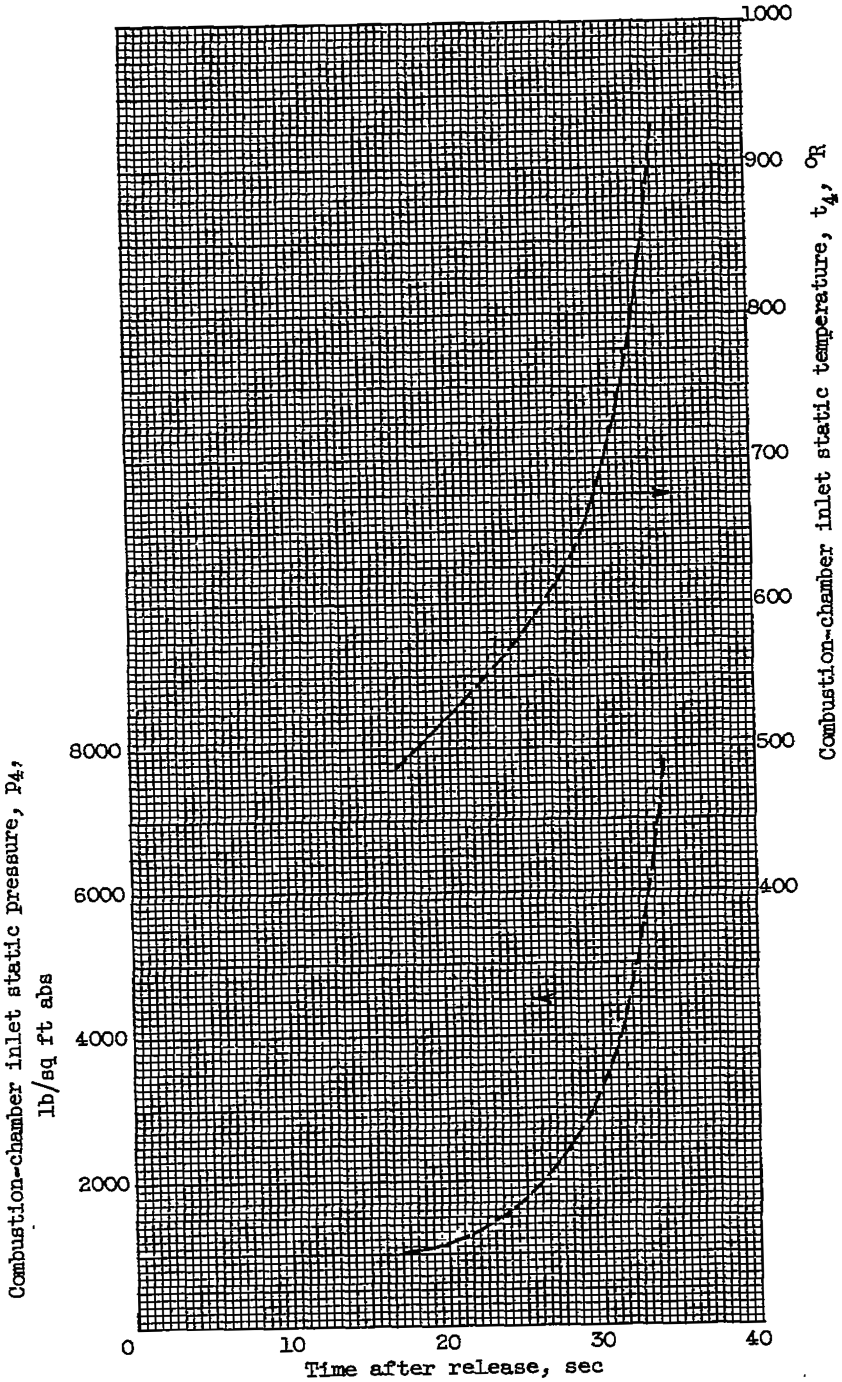

(b) Inlet static pressure and temperature.

Figure 7. - Concluded. Time history of combustion-chamber conditions.

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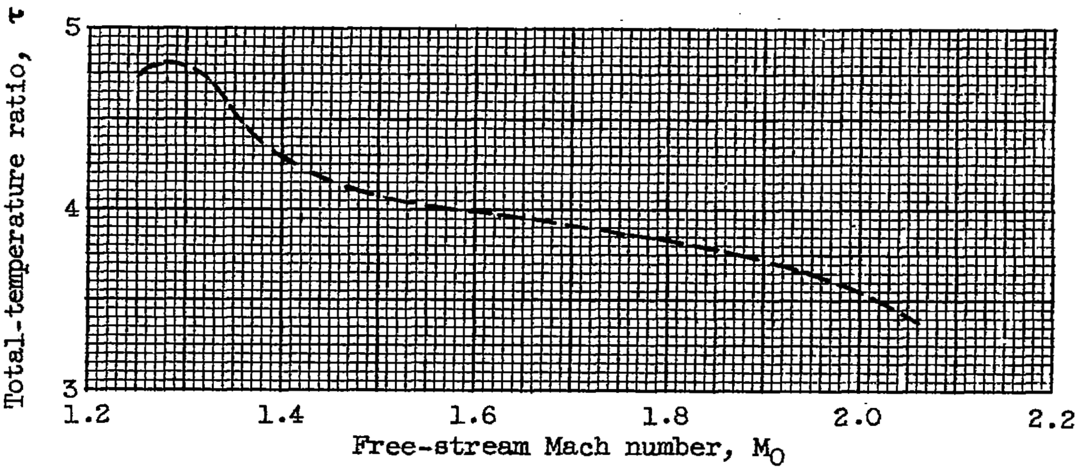
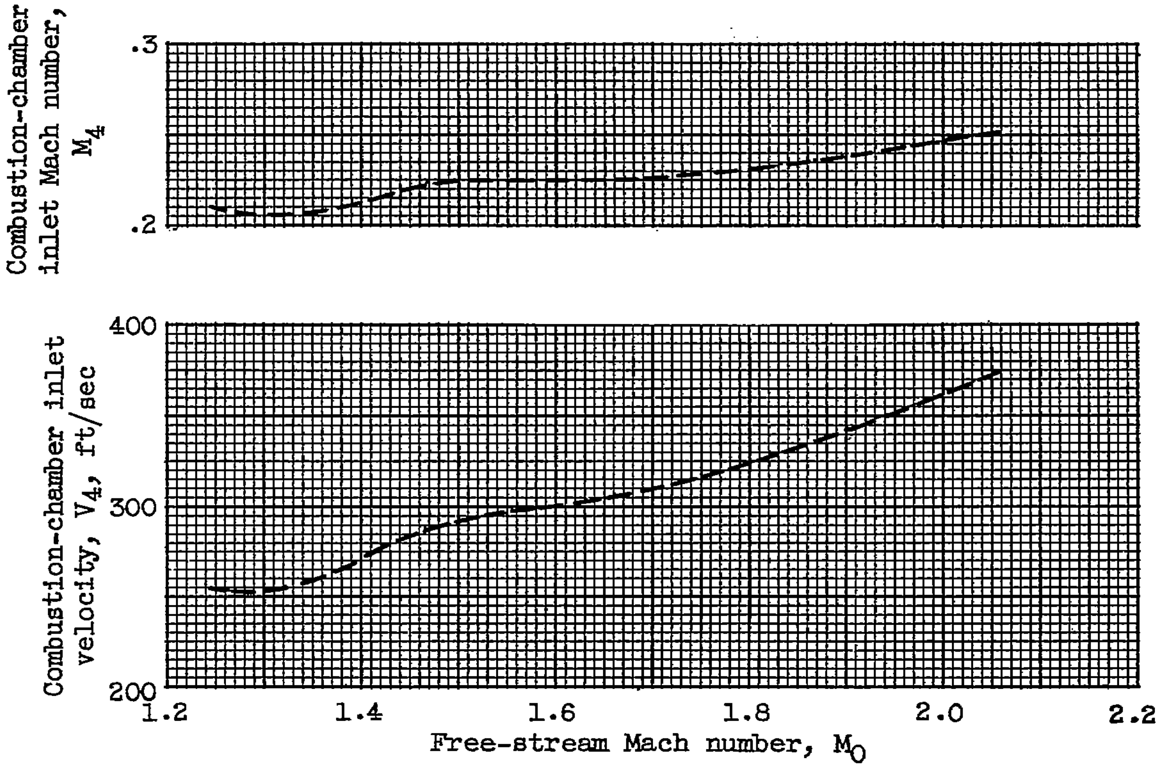


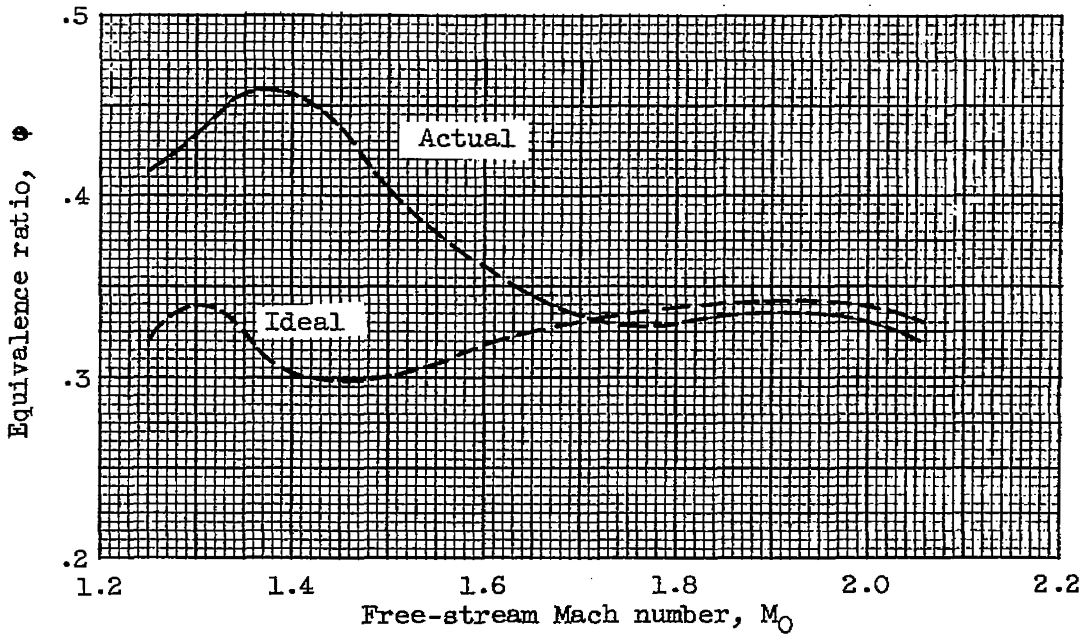
(a) Total-temperature ratio.

Figure 8. - Variation of combustion-chamber conditions with free-stream Mach number.



(b) Inlet Mach number and velocity.

Figure 8. - Continued. Variation of combustion-chamber conditions with free-stream Mach number.



(c) Equivalence ratio.

Figure 8. - Concluded. Variation of combustion-chamber conditions with free-stream Mach number.

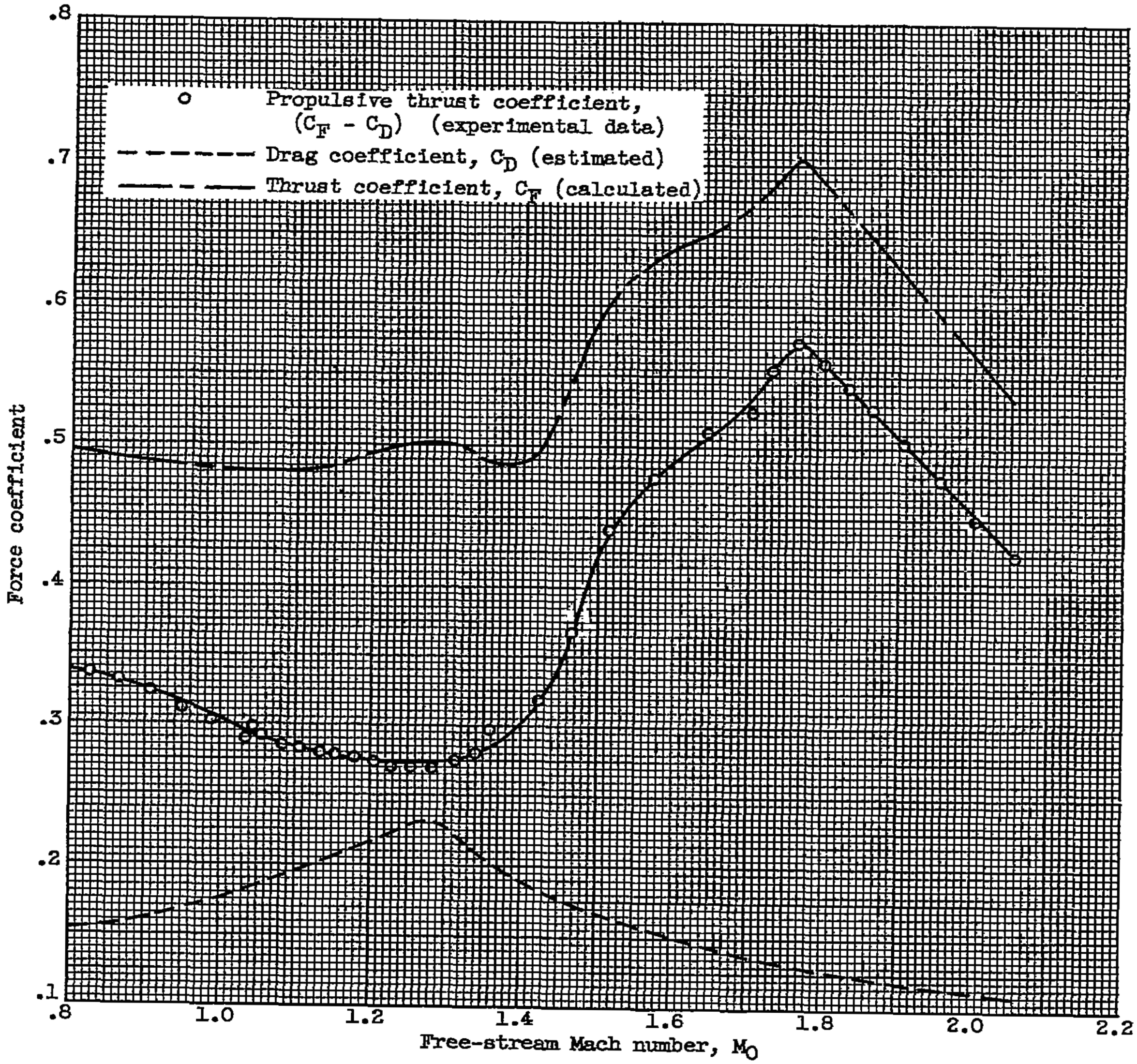


Figure 9. - Propulsive thrust, drag, and thrust coefficients as a function of free-stream Mach number.

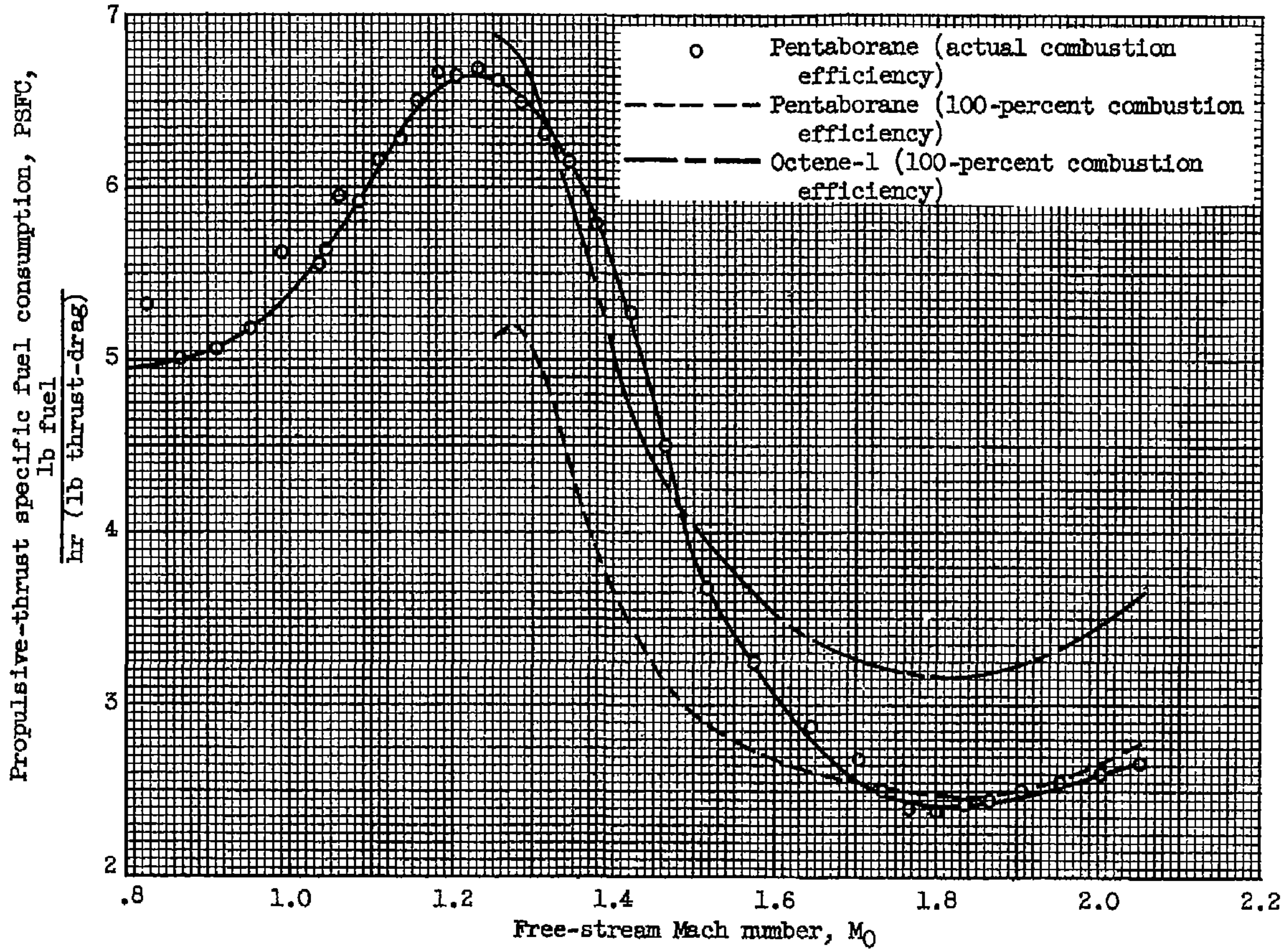


Figure 10. - Propulsive-thrust specific fuel consumption as a function of free-stream Mach number.

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